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The Road from the NASA Access-to-Space Study to a Reusable Launch Vehicle

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Abstract

NASA has established a goal of providing low-cost reliable access to space. While this goal has been around for many years, it received a major impetus when the U.S Congress mandated the Access-to-Space study in 1993. This study concluded that a rocket powered single-stage-to-orbit vehicle offered the best opportunity for low-cost reliable space transportation by the first decade of the new millennium. This required a focused technology development program before such a vehicle could be built. NASA recognized that no commercial entity would commit to the development of a single-stage-to-orbit vehicle without the U.S. Government's participation. To this end, NASA entered into a cooperative agreement with industry to mature the required technologies. This effort includes the development of an experimental subscale-vehicle known as the X-33, an extensive ground-based program to provide the required additional technology development, and conceptual through preliminary design of an operational reusable launch vehicle. Following this effort, a decision will be made whether or not to proceed with the detailed design and fabrication of an operational vehicle.

Introduction

NASA is cooperating with the aerospace industry to develop a space transportation system that provides reliable access-to-space at a much lower cost than is possible with today's launch vehicles. While this quest has been on-going for many years it received a major impetus when the U.S. Congress mandated as part of the 1993 NASA appropriations bill that: "In view of budget difficulties, present and future... the National Aeronautics and Space Administration shall ... recommend improvements in space transportation." This led to the "Access-to-Space" study (Ref. 1) which concluded that the best opportunity to reduce launch costs, and improve safety and reliability was to develop a fully reusable single-stage-to-orbit vehicle capable of delivering 25,000 lb to the International Space Station. The study identified many technologies that had to be matured before a commitment could be made to build such a vehicle. NASA accepted the recommendation and the need for new technology as the key to low-cost, reliable space transportation. A decision was also made by NASA that it should purchase future launch services and no longer operate a Space Transportation System. To meet the objectives of a low-cost, reliable, commercially owned space transportation system, NASA believes that the required technologies must be matured sufficiently before a commercial organization will commit the financial resources required for development. To aid in this maturation process, NASA entered into a cooperative agreement with Lockheed Martin Corporation to develop the X-33. The X-33 is a half-scale demonstrator of a single-stage-to-orbit, all rocket-powered vehicle. The X-33 will demonstrate the implementation and testing of many of the required technologies. In addition to the X-33, NASA has funded ground-test programs for the critical technologies, and conceptual through preliminary design studies for the operational reusable launch vehicle. The combination of the X-33, the ground-based program and reusable launch vehicle studies are expected to provide the necessary information to determine the viability of a commercially developed launch vehicle. This information will be available soon after the turn of the century. This paper will discuss the results of the access-to-space study, expected results and status of the X-33, the ground test programs, and the reusable launch vehicle study.

**Senior Aerospace Engineer.*

Nomenclature

CFD	Computational Fluid Dynamics
cg	center of gravity
FY	Fiscal Year
H2	Hydrogen
LH2	Liquid Hydrogen
LOX	Liquid Oxygen

NASA	National Aeronautics and Space Administration
O/F	Oxidizer to Fuel ratio
O2	Oxygen
RLV	Reusable Launch Vehicle
TPS	Thermal Protection System
USAF	United States Air Force

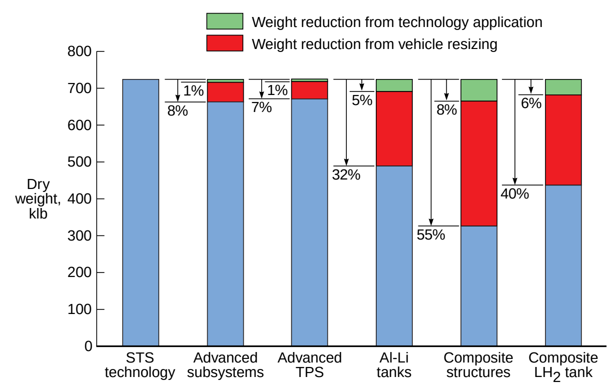
Access-to-Space Study

The FY 1993 NASA Access-to-Space objective was to identify the best space transportation architecture that would result in significant cost reductions, while increasing safety and reliability. NASA, working with other organizations, including the Department of Transportation, and the Department of Defense, identified three major transportation architecture options to be evaluated in the areas of reliability, operability and cost. These architectural options were: (1) retain and upgrade the Space Shuttle and the current expendable launch vehicles; (2) develop new expendable launch vehicles using conventional technologies, and transition to these new vehicles beginning in 2005; and (3) develop new reusable vehicles using advanced technology, and transition to these vehicles beginning in 2008. The launch needs mission model was based on 1993 projections of civil, defense, and commercial payload requirements through the year 2030. Each of the architectural options was studied by a separate team working independent of each other. Uniform costing guidelines were developed to allow direct comparison of the results of the three teams. A small group reporting to the study director assessed each team's recommendations. This "Access-to-Space" study concluded that the architecture option that provided the greatest potential for meeting the cost, operability, and reliability goals was a rocket-powered single-stage-to-orbit fully reusable launch vehicle (RLV) fleet designed with advanced technologies.

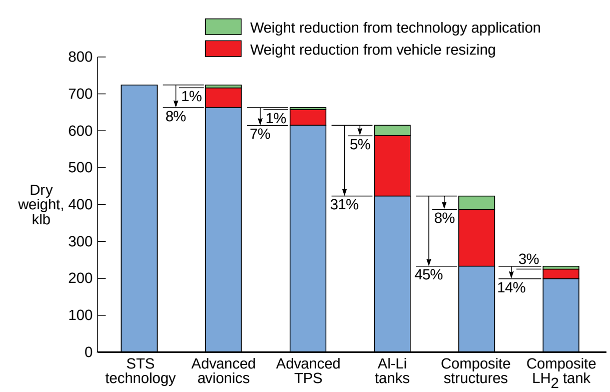
The Access-to-Space study determined that this RLV vehicle would need many advanced technologies to be viable. Those technologies identified that are not at the required maturity levels are:

1) Graphite-composite reusable primary structure
2) Aluminum-lithium and graphite-composite reusable cryogenic propellant tanks
3) Advanced main propulsion systems designed for robustness and operability. (In terms of performance, the Space Shuttle main engines are adequate both in specific impulse and thrust to weight ratio. Again, the issue being addressed is robustness and operability.)
4) Low-maintenance thermal protection systems
5) Advanced avionics that include vehicle health monitoring and autonomous flight control.

Advanced technologies that contribute to the vehicle's dry weight reduction are critical, because dry weight is a major cost driver. The effect of selected technologies on the vehicle's dry weight can be seen in figure 1. The mission for the baseline vehicle was to deliver a 25,000 lb payload to the International Space Station (ISS) in 220 n.mi. circular orbit inclined at 51.6°. (ISS orbit has since been changed to 248 n.mi. circular orbit at 51.6°.) Figure 1a shows the effect of each technology added individually to the baseline vehicle designed using Space Shuttle technology. The green bar at the top of each bar represents the weight reduction that occurs by simply replacing the equivalent Space Shuttle technology with the advanced technology. Then, since the vehicle can now be redesigned using this technology, there is a multiplicative effect of weight reduction as shown by the red bar. For instance all systems can now be resized to account for the overall reduced weight, thus the landing gear is lighter, the wing smaller and lighter, the tanks smaller (less propellant required to reach orbit), etc. The lighter bar shows this multiplicitive effect. Note that there are relatively small weight benefits due



a. Individual effect.



b. Cumulative effect.

Figure 1. Effect of advanced technologies on RLV.

to advanced avionics and thermal protection systems. The advancements in these areas were primarily for operability and reliability, not weight reduction. An additional note, for this study the advancements in main propulsion systems was assumed to provide no weight reduction, but only improved operability and reliability. This chart shows that the advanced cryogenic tanks and the use of composite structure instead of aluminum offer the largest weight reductions. Figure 1b shows the impact of the cumulative effect of these technologies. It shows that if all these technologies mature as projected, it would be possible to build a RLV to do the design mission with a dry weight near 200,000 lb. This dramatic effect of technology improvement was the primary justification for the Access-to-Space study conclusion.

NASA elected to proceed with the development and demonstration of the technologies that would enable a rocket-powered single-stage-to-orbit reusable launch vehicle through a cooperative agreement with industry. The implementation of the "Access-to-Space" plan is known as the Reusable Launch Vehicle (RLV). The RLV program was established to be a cooperative effort between NASA and aerospace companies, and marks a significant departure from the way NASA implements programs. In this cooperative agreement NASA and the selected contractor(s) each provide part of the funding required. In addition, the selected contractor(s) hire NASA centers to perform specific tasks. Note that these cooperative agreements put the decision authority in the hands of the contractors, not NASA. NASA is assisting industry with the development of the "high-risk technologies that industry cannot afford." said Goldin, the NASA Administrator, "But NASA won't build the vehicle, industry will. NASA will be a user, not an operator." The RLV is to lead to a commercialization of space access with more airplane-like operations, such that the cost of delivering payload to orbit is significantly reduced. The goal is to decrease the cost to deliver payload to low earth orbit from the current estimated $10,000 per pound to $1,000 dollars per pound.

The RLV program is structured in three phases. In Phase I, which began in March 1994, U.S. aerospace contractors developed conceptual-level vehicles - both operational vehicles and a corresponding technology demonstration vehicle; technology requirements; demonstration and operational vehicle development plans; and business plans detailing how the contractor would commercialize the RLV. This activity also included the demonstration of many key sub-scale technologies, including the first successfully tested large scale graphite composite liquid hydrogen tank, automated checkout of the main propulsion system, and advanced, durable ceramic and metallic thermal protection systems. The Phase I effort was the preparation of contractor proposals to NASA for Phase II funding. Three contractors, Rockwell International, McDonnell Douglas and Lockheed Martin worked in cooperation with NASA on the Phase I effort. Lockheed Martin Skunk Works (LMSW) was awarded the Phase II contract on July 2, 1996. The Phase II RLV industry team includes LMSW as prime, Rocketdyne as engine subcontractor, BF Goodrich as thermal protection system contractor, and Allied Signal as subsystems contractor.

The X-33 Program

The X-33 Program is demonstrating the key design and operational aspects of a single-stage-to-orbit (SSTO) reusable launch vehicle (RLV) rocket system so as to reduce the risk to the private sector in developing a commercially viable system. The X-33 program is implementing the National Space Transportation Policy, specifically Section III, paragraph 2(a): "The objective of NASA's technology development and demonstration effort is to support government and private sector decisions by the end of this decade on development of an operational next-generation reusable launch system."

In order to meet its objectives, the X-33 program is a very aggressive, focused launch technology development program. It has extremely demanding technical objectives and equally demanding business objectives.

The primary objectives of the X-33 program are:

- Implementation of technology demonstrations (flight and ground) so as to reduce the business and technical risks, which will enable privately financed development and operation of a next generation space transportation system.

- The X-33 flight system, subsystems, and major components shall be designed and tested (in flight and ground) so as to ensure their traceability to a full scale SSTO rocket system. Technical objectives also include improved mass fraction for vehicle structures and improved thrust to weight for rocket propulsion systems.

- The X-33 system must demonstrate key "aircraft like" operational attributes required for a cost effective SSTO rocket system. At a minimum, key demonstrations will include: operability (e.g., improved thermal protection system (TPS) robustness, all weather operation, reduced maintenance requirements, etc.), reusability, affordability, and safe abort.

One of the key elements of the Phase II program is the development, design, fabrication and flight testing of the X-33. Technologies to be demonstrated by the X-33 were defined directly by the technology requirements of the VentureStar. Thus X-33 was defined by traceability requirements to VentureStar. The X-33 is an approximately half scale vehicle as compared to VentureStar.

As depicted in figures 2 and 3, the Lockheed Martin Skunkworks is building a vertical takeoff, horizontal landing lifting-body configuration. This vehicle relies on its lifting-body shape to provide a significant percentage of the aerodynamic lift during entry. Another unique aspect of this configuration is the use of a linear aerospike main engine system integrated with the lifting-body shape. This engine was an alternate to the current Space Shuttle Main Engine in the early stages of Space Shuttle development.

a. Front view.

b. Rear view.

Figure 2. X-33 configuration.

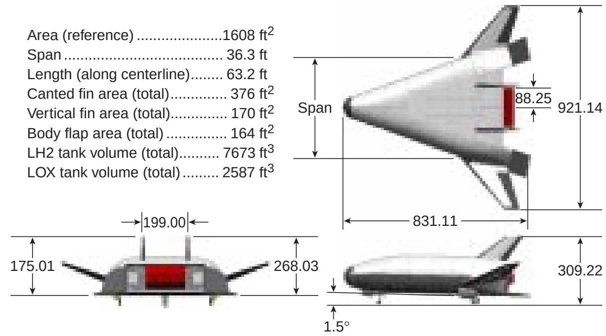


Figure 3. X-33 three view.

As is illustrated in Figure 4, the X-33's load carrying structure consists of the integrated thrust structure, cryogenic tanks, and intertank structure. Secondary structures like control surfaces, and TPS are attached to primary structure. Structural integrity and load paths are verified by finite element modeling and structural development testing. Aerodynamic and aerothermal loads are developed from CFD analysis and wind tunnel test and will be verified in flight tests.

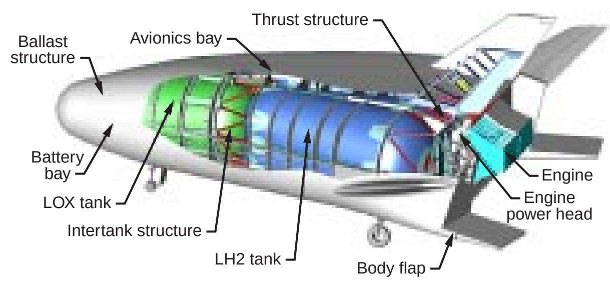


Figure 4. X-33 Internal arrangement.

Key technologies that will be demonstrated by X-33 flight vehicle include:

- Low cost operations with rapid, safe turnaround of the vehicle

- Autonomous ascent, reentry and landing

- Graphite composite multilobe liquid hydrogen tanks

  As illustrated in figure 5, the X-33 composite liquid hydrogen (LH2) tank is a quad-lobe tank including frames and insulation. The X-33 tanks are produced in existing autoclaves to demonstrate tank producibility. The tank material IM7/997-2 was tested for and passed permeability in previous testing. Tank sealing between the tank quarter sections is accomplished using a woven composite web "y" joint.

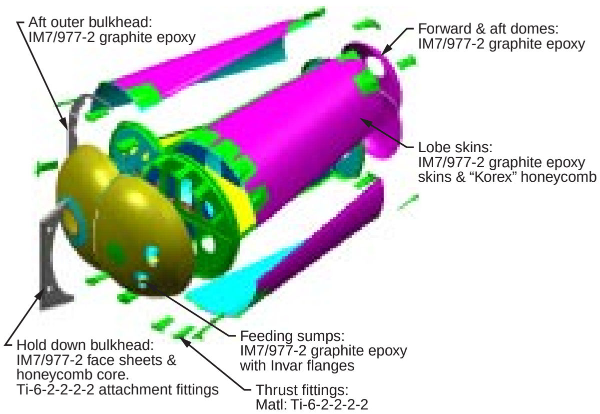


Figure 5. X-33 Composite liquid hydrogen tank (1 of 2).

- Graphite composite primary airframe system

- Metallic thermal protection systems

  The TPS must keep the temperature of the interior tanks and body support structure at or below 350°F. Figure 6 illustrates the placement of TPS on the X-33.

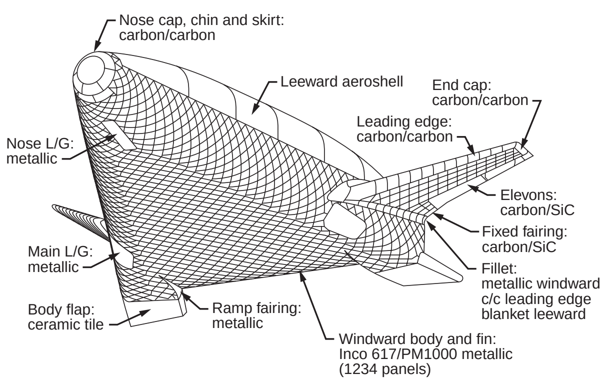


Figure 6. X-33 thermal protection systems.

  The majority of the windward side of the vehicle uses inconel 617 honeycomb panels packaged into 26" × 22" diamond panels. PM 1000 metallic panels are used in a limited number of higher temperature areas. Carbon carbon is only used for the nose area and control surface leading edges and ends. The upper surface are composite panels covered with ceramic blankets. A lapping shingle seal is used between panels to prevent hot gas leakage into the interior of the vehicle.

- Lifting body flight from subsonic to hypersonic speeds

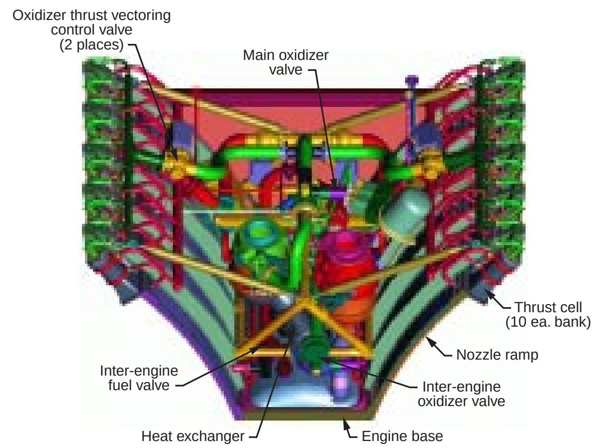
  The X-33 draws its aerodynamic heritage from a series of lifting bodies developed in the 1960's and 1970's, including the M2 series HL-10 and X-24 series (Ref. 2).Typical lifting body shapes allow for the elimination of a separate wing structure (Wings or low dihedral canted fins are required on the rocket-powered SSTO configuration due to the aft mounted engines.) The objective of the lifting body is to increase the effective area of lift, thereby decreasing the heating on the body upon reentry. This, combined with large body radii, allows for the use of lower temperature, but more durable metallic thermal protection systems over a large portion of the X-33.

- Aerospike rocket engine

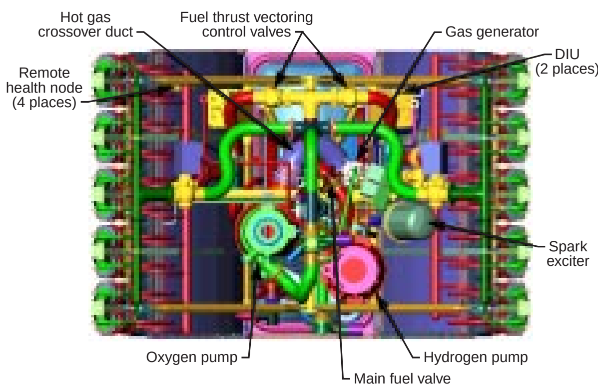
  The X-33 main propulsion system uses an aerospike nozzle. The aerospike engine fills the base of the vehicle, reducing base drag, and is integral to the vehicle, reducing installed weight. The aerospike draws its heritage from over $500M of investment in aerospike rockets by NASA, the USAF and Rocketdyne beginning in the late 1960's. The X-33 engine uses turbomachinery from the J-2S rocket engines (Ref. 3), which were used to power the Apollo Saturn V S-II, and S-IB stages. Several J-2S engines remaining from the Saturn program were disassembled, components refurbished and incorporated into the X-33 engine.

  The enhanced performance of the aerospike is due to the external expansion of combustion gasses. It's plume is open to the atmosphere on one side and free to move, allowing the engine to operate at its optimum expansion at all altitudes. It compensates for decreasing atmospheric pressure as the vehicle ascends, keeping the engine's performance high throughout the entire trajectory. This altitude-compensating feature allows for a simple, low-risk gas generator cycle. The aerospike is designed to exhaust the gasses through the truncated end of the spike, creating additional thrust (i.e., aero-spike)

  Four engines will be built for the X-33. Two will be installed on the vehicle, and two used for testing with one of the two engines to be rebuilt and used as a spare. As illustrated in figure 7, each of the two engines on the X-33 will have a series of 20 modular combustion chambers – ten aligned along the forward end of each nozzle ramp – and will produce 206,500 pounds of thrust at sea level. Table 1 describes several other key characteristics of the engine.



a. Side view.



b. Top view.

Figure 7. X-33 Main engine (1 of 2).

Unlike the Space Shuttle main engines which use heavy and complex hydraulics to direct the thrust vector of the engine, the X-33 modulates the flow to the thruster bank on each side of the engine for pitch, spools each engine's thrust up or down for yaw and uses a combination for roll.

- Avionics systems based on micro-electromechanical technology developed for NASA's deep space scientific missions.

Innovative management methods are another "technology" being utilized and demonstrated on the X-33 program. From contract award, the program had 36 months to design and build an X-33 – unheard of for a vehicle of this complexity and a program of this magnitude, i.e. 29 organizations in 16 states. A Cooperative Agreement is used between NASA and the industry partner, the Lockheed Martin Skunkworks, to describe the responsibilities of NASA and Lockheed as well as mile-

Table 1. X-33 Main Specifications

Thrust, lb	
At sea level	206,500
In vacuum	268,000
Specific impulse, sec	
At sea level	339
In vacuum	439
Propellants	O2, H2
Mixture ratio (o/f)	5.5
Chamber pressure, psia	857
Cycle	gas generator
Area ratio	58
Throttling, percent thrust	40~119i
Differential throttling	±15%
Dimensions, inches	
Forward end	133 high × 88 wide
Aft end	46 high × 88 wide
Forward to aft	79

stones and criteria for payment to the partner (through payment milestones). Successful implementation of this program requires both NASA centers and Lockheed Martin to commit to technical task accomplishment within a fixed set of cost and schedule constraints. Concurrent engineering is utilized to reduce vehicle development and fabrication cost by significantly reducing the time between initiation of the program and first flight. The core team is co-located at the assembly site in Palmdale, California with design, manufacturing and operations disciplines being involved in product teams from program initiation. Lessons learned from the concurrent engineering process in X-33 will be applied to the reusable launch vehicle. The extent of concurrent engineering for RLV will be a balance between technical feasibility and cost.

X-33 flights are planned to start in July 1999. 15 flights are planned for completion by December 1999. The X-33 will be launched vertically from Edwards Air Force Base, California. The first flights will land horizontally at Dugway Proving Ground, Utah with later higher Mach number flights planned for Malmstrom Air Force Base, Montana. The X-33 Critical Design Review was completed at the end of October 1997, which signaled the go-ahead for completing component fabrication and assembly of the X-33. Daily progress of the X-33 can be viewed on the X-33 internet web site at http://x33.msfc.nasa.gov.

RLV Technology and Vehicle Design

The decision to develop and build an operational RLV, through initiation of Phase III will be based on: 1) an evaluation of the technology readiness demonstrated through X-33 flight vehicle and ground-based programs; 2) existence of a vehicle and infrastructure design demonstrating technical feasibility, at a level of maturity required to pass a preliminary design review; 3) determination of the cost to assess commercial viability, as well as the existence of a business plan; and 4) a plan for transitioning from the current Space Shuttle to the RLV.

Though the X-33 flight demonstrator will go a long way toward demonstrating the flightworthiness of technologies critical to a reusable launch vehicle, there are a number of technology development efforts and ground tests required to demonstrate technology not tractable for inclusion in the X-33. Phase II, as mentioned above, also includes many of these technology development and ground test demonstration efforts.

Although the X-33 will demonstrate the critical performance and thrust vectoring characteristics of the aerospike engine, several technologies required for an operational aerospike rocket engine, crucial to a successful RLV decision, will not be demonstrated on the X-33. A significant element of ground activities will be to develop and demonstrate a full scale, flight weight powerpack (gas generator and turbopump assembly) and composite lightweight nozzle.

Additional ground-based development of the oxidizer and fuel tanks are also required for the RLV. The LOX tank on X-33 is aluminum but planned to be composite for the VentureStar. Therefore, a subscale RLV LOX tank will be developed and ground tested. Issues such as LOX compatibility, design for minimum weight, load carrying capability and durability to certify their life cycle for 100 flights, scale effects, producibility and health monitoring will be addressed. Non-autoclave large scale, conformal structures for both the LOX and LH2 tanks will be addressed. For example, although the liquid hydrogen tanks on the X-33 are composite, they are small enough to enable fabrication in existing autoclave facilities. Due to the scale-up required for RLV, other methods must be considered to identify the most cost effective and technically feasible fabrication process.

Development of the metallic thermal protection system is in progress as part of the X-33 program. Trades are on going to improve the thermal protection system beyond that which will be flown on the X-33. Issues such as minimizing weight, design to withstand the thermal environments, and sealing are currently being addressed. As an example, the X-33 design uses seals on the outer surface of the vehicle, thus carrying the pressure loads on the structure of the seals themselves. Alternate concepts, with similar weights, have been identified that seal the TPS on the lower surface of the panel along a lattice framework, reducing the risk of hot gas ingestion into the vehicle. Material development and more efficient integration of the thermal protection system with the tanks are also being pursued to minimize the overall weight of the system for RLV.

As noted, most of the technology development efforts discussed above have dry weight minimization (which leads to cost minimization) as one of their primary goals. For the X-33, weight control is critical to achieving the flight environments necessary to obtain the range of data required for application to the RLV. However, as critical as weight management is for the X-33, it is much more critical for the VentureStar. If the X-33 does not achieve its weight goals, the primary objective of technology demonstration may still be achieved, but if the VentureStar does not achieve its weight goals, its viability as a cost-effective launch vehicle is reduced. VentureStar must deliver the payload to the delivery orbit. For example, one of the primary mission requirements is the delivery of a 25,000 lb payload to the International Space Station. For a fixed size vehicle, every pound of extra weight added to the VentureStar structure, or engine, or subsystems, is one less pound of payload that can be delivered to orbit. It doesn’t take much weight growth before the payload weight allowance is consumed. During the design process, the vehicle can be scaled up to gain back the payload capacity only to a point. The vehicle must remain within the size limitations projected by the business sector to ensure the required level of operability and profitability.

Aside from critical technology development there are additional ways to minimize the dry weight of a vehicle for a given mission. For example, selection of the configuration sets the stage for the minimum weight achievable. The overall packaging concept of the configuration must have inherently efficient load paths, in particular from the engine through the tanks, to minimize structural weight. In addition the vehicle must have a shape that minimizes flyability and aerothermal issues. Once the vehicle configuration is defined, trades and parametrics can be run from that baseline to maximize the efficiency of the detailed integration and performance.

Several trade studies have been completed on VentureStar within the basic configuration concept, significantly reducing the dry weight of the vehicle. (It should be noted that these trades are on going, given that the Preliminary Design Review for VentureStar is planned for December of 1999.) For example, like the X-33, the original tank layout for the VentureStar was a LOX forward configuration with two quad lobe LH2 tanks behind the LOX tank, with the payload bay fully imbedded behind the LOX tank and between the two LH2 tanks. Trade studies have shown that a significant reduction in vehicle structure and LH2 tank weight can be achieved by combining the two LH2 tanks into one multilobe tank with the payload protruding part way out of the top of the vehicle. The weight reduction is primarily due to a reduction in the surface area of the tanks and vehicle, and an increase in the vehicle packaging efficiency.

Another example of the improvements made to the VentureStar is the improved integration of the tanks with the thermal protection system. Stand-off distances and the corresponding structure between the outer moldline of the tank and the outer moldline of the TPS has been reduced, resulting in a further improvement in the volumetric efficiency of the vehicle. The vehicle is also being designed to maximize TPS panel commonality, leading to a reduction in cost. For example, the vehicle is being designed with a flat bottom and a common radius along the chines of the vehicle all the way from the nose to the aft end.

Requirements to minimize vehicle weight through improved vehicle packaging, load paths, integration, and engine thrust to weight, to name a few, have a direct tie to the outer moldline and center of gravity (cg) of the vehicle. One of the challenges of VentureStar, present in varying degrees in any single-stage-to-orbit rocket-powered launch vehicle, is the ability to achieve across the Mach range flyability, i.e. trim and control. The challenge is greatest on entry where the vehicle is inside the atmosphere from hypersonic speeds through landing. In addition, trajectories must be constrained to meet aerothermal constraints and cross range and landing requirements. Adding to the challenge, the aft engine mounted SSTO configuration results in an entry weight cg far aft on the vehicle. X-33 had the luxury of including ballast in the nose of the vehicle to move the cg forward. The addition of ballast is undesirable in the VentureStar where minimizing vehicle weight is so critical. The result is a vehicle flying over a large Mach range, over a wide constrained range in angle of attack, with a short moment arm between the aft mounted control surfaces and the vehicle center of gravity. The wings, tails and control surfaces must be designed and sized to counteract the aerodynamic moments generated by the body, enabling both trim and control at all flight conditions, while minimizing additional weight.

The VentureStar outer moldline development is being done with across the Mach number aerodynamic screening. Rapid turn around aerodynamic testing can be accomplished subsonically and hypersonically with stereolithography models, however transonic and supersonic testing require longer lead-time metal models. Testing in the transonic regime is critical however, particularly for development of the lifting body configuration. For example, as seen in the X-33, the transonic Mach tuck can be one of the flight conditions that defines the design of the control surfaces and/or body shaping. Transonic Mach tuck is defined as a nose down pitching moment that occurs as a vehicle goes through transonic speeds. It results from the distribution of shocks over a vehicle. The nose down moment can be so severe that modifications to the aerodynamic lines of the vehicle are required, or control surfaces sized, to enable trim and control through that flight regime. Camber was eliminated from the VentureStar body to reduce the Mach tuck phenomenon. The effectiveness of the change was verified through tunnel testing.

In addition to development of the configuration, a significant amount of benchmark wind tunnel testing will be required to build the aerodynamic and aerothermodynamic databases for the RLV. The test time will be required not only to formulate the databases, but to minimize the uncertainty in these databases across the entire VentureStar flight envelop. Given the weight targets, uncertainty must be minimized as much as is feasible such that unnecessary margin, for example in control surface or RCS thruster sizing, can be safely eliminated. In other areas, efforts to employ operationally robust lower weight, lower temperature TPS, to protect against the nominal and dispersion aerothermal environments, must be assessed to assure mission success while minimizing weight and cost.

Computational methods are also being used to assist in the development of the configuration. Solution times for unstructured Euler CFD solutions are approaching those required for use within the short design cycle times. Several regions of the flight corridor are viscous dominated however and the longer solution time Navier Stokes solutions are required to provide accurate computational-based forces, moments and loads. Computational methods are also being used to provide aerothermal environments. Boundary layer methods coupled to Euler solutions are used to provide more rapid environments while Navier Stokes solutions are used for more detailed higher fidelity results.

Before the VentureStar outer moldline is frozen, additional trades on the design are being completed. For example, a trade is on-going to identify the optimum included angle of the lifting body planform. The trade encompasses the sensitivity to aerodynamic drag on ascent, packaging efficiency, aerodynamic characteristics and control surface sizing, as well as aerothermal environments on entry with the impact on TPS sizing. Performance trades are also in progress to identify the optimal vehicle oxidizer to fuel weight ratios, lift-off thrust to weight, thrust vector only vs. blended thrust vector/aerosurface control on ascent, entry control strategies, and development of abort capabilities, to name a few. All efforts are being made to minimize the weight of the vehicle to meet the payload and mission requirements. It is also imperative that the vehicle be designed with enough weight margin in the early phases to ensure a commercially viable reusable launch vehicle. Figure 8 shows one of the early versions of the VentureStar configuration.

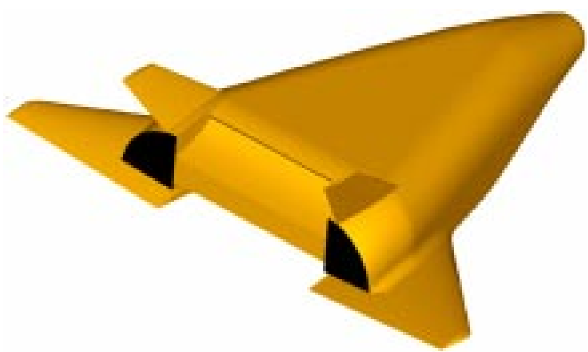


Figure 8. Preliminary RLV configuration.

Summary

A partnership between NASA and U.S. aerospace companies has been established to meet the goal of low-cost, reliable space transportation. The path was identified by the Access-to-Space study performed under NASA's leadership in 1993. The Access-to-Space study determined that the most effective solution, to meet the goals by the first decade of the new millennium, was an all-rocket-powered single-stage-to-orbit-vehicle. However, the study also determined that today's technologies were inadequate. A focused technology program was initiated through the NASA-industry partnership to develop, fabricate and flight test the X-33, a subscale technology demonstrator for the operational vehicle along with a ground-based program for further technology development and the conceptual through preliminary design of the operational vehicle. This activity will lead to a decision on whether or not to proceed with the detailed design and build of an operational vehicle.

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